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# Use of Pulsar Signals As Clocks

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The pulses of energy from pulsars are regarded as ticks from a clock. By comparing this pulsar clock with an earth-based atomic clock, several variations in the pulsar clock's frequency are noted. The major effect is due to the motion of the atomic clock in relation to the pulsar clock and contains information on the pulsar's position, elements of the earth's orbit, and solar relativistic effects. Another effect is the slowly varying frequency of the pulsar clock and contains information on the physics of the pulsar. In this article, the measurements of these effects and their present and future applications are discussed.

## Introduction

One of the remarkable properties of pulsars is the emission of periodic pulses of energy. The periods of the known pulsars vary from 0.033 to 4 s. The periods are also slowly increasing with a typical value of 200 ns/yr. If these pulses are regarded as ticks of a clock, this pulsar clock can be calibrated with great accuracy.

Shortly after the discovery of pulsars, a program was started in order to see how well these pulsar clocks could be calibrated. The Venus Deep Space Station (DSS 13) at Goldstone is an ideal environment in which to conduct the measurements. The low-noise maser receiver and the high-rate sampling ability of the station are ideally suited to the measurements. The S-band operating frequency also minimizes charged-particle effects on the received pulse train.

The observations of the arrival times of the pulses are made using a 26-m parabolic reflector at a frequency of 2388 MHz. The atomic clock used to record the time-of-arrivals is a cesium standard, which is compared monthly with the master clock at the National Bureau of Standards.

The observational technique has been described elsewhere (References 1 and 2) and will not be described here. The sampling resolution of the pulses is typically on the order of 100 $\mu$s.

The determination of the arrival time for each pulse is accomplished by correlation techniques. The signal-to-noise ratio for the pulses is improved by coherently adding at least 500 pulses. The pulse is then correlated with a template which approximates the pulse shape. The determination of the arrival time has been described more fully in References 1 and 2. Typically, they have a standard deviation on the order of 100 $\mu$s.

An initial application of the pulsar clock was the synchronization of earth-based clocks. The application of this technique to the Deep Space Network seemed attractive since only an antenna to receive and a correlator are needed, i.e., a passive measurement. The technique is not presently competitive with the moon-bounce technique, due to the present limitation on sampling resolution and the noise on the pulses. Work is currently being done to develop a technique to sample the pulses faster.

The determination of the pulsar's positions and period characteristics has proved of value to the scientific community. Several groups of optical observers have used our positions and periods to try to detect pulsars optically. The period characteristics have been used by the scientific community to try to explain some of the physics of pulsars.

An attempt has also been made to measure the sun's gravitational red shift. The magnitude of the effect is easily within the measurement accuracy but has so far eluded detection due to correlation problems. A technique to eliminate these correlations and make a definitive measurement is currently being worked on.

With improved sampling resolution, elements of the earth's orbit can be improved. At present most of the measurable parameters are better measured by planetary radar. The parameter of the earth's orbit that can best be measured by pulsar clocks is the orientation of the orbit with respect to the celestial sphere. These measurements are currently made using a combination of optical and radar measurements.

## Problem Formulation

The period characteristics of the ticks from the pulsar clocks, as observed at Goldstone, are different from those of the emitted ticks. Of interest are the differences, as well as the period characteristics, of the emitted ticks. The differences between the emitted and received period

characteristics can all be attributed to the motion of Goldstone in the inertial frame of the solar system (within measurement accuracy).

The inertial frame used for the calculations is a right ascension–declination system for the epoch 1950.0 centered at the barycenter of the solar system. The ephemeris used to describe the motion of the geocenter about the barycenter is JPL ephemeris DE-69 (Reference 3). The motion of Goldstone about the geocenter, the conversion from ET (ephemeris time) to UTC (universal time coordinated), and the reduction to the epoch 1950.0 were computed by means of standard equations using parameters developed at JPL (Reference 4).

To remove the effects of Goldstone's motion, the arrival times of the ticks were reduced to the barycenter of the inertial frame. The line element used to make the reduction is the Robertson isotropic line element which is consistent with DE-69. This allows us to account for relativistic effects on the arrival times, such as delay in the solar gravitational field and the red shift of the atomic clock as it moves in the solar gravitational field.

The pulsar's angular position is needed in order to make the reduction to the barycenter. Changes in the period due to changes in the relative distance between the barycenter and the pulsar are indistinguishable from the emitted period for motion on the order of galactic rotation (Reference 2). This is not true if the distance varies in a rapid (in the galactic sense) manner such as if the pulsar were in orbit. Proper motion and distance can also be detected in a manner similar to optical techniques.

The period characteristics are described by means of a polynomial that is equivalent to a Taylor series expansion of the period. The period is given as a function of time from some initial epoch. This form of representation is convenient since other models can be related to our model by simply comparing the derivatives.

A mathematical model has been constructed which includes all of the above-mentioned effects as free parameters. This model is used to predict the time-of-arrival of ticks at the barycenter of the inertial frame. These predictions are compared with the observations and the model is then differentially corrected by least-squares techniques.

Currently, 20 pulsars are being observed on a regular basis. Solutions of the parameter sets for 12 pulsars have been obtained (References 2 and 5), and work is continuing on the remaining 8, as well as on the first 12 for improved solutions. Since the major solar system effects on the arrival times of the ticks are tied to the earth's motion about the sun, a year's worth of data is typically required to obtain a minimal correlation solution.

## Results

Specific numerical values for the results that were obtained in this study are given in References 2 and 5. Our main interest here will be with the precision of the results and the limits of this precision. Our discussion will be limited to only typical results and not for any one pulsar.

Regarding position determination, definitive results have been obtained for angular position only. After a year's worth of data, the typical limitation is the accuracy of the ephemeris of 0.1 seconds of arc in right ascension and declination. This limitation is due to the uncertainty in reducing the data to the inertial frame. The typical relative uncertainty is on the order of a few hundredths of a second of arc. Bounds have been determined for proper motion and distance (Reference 6). A typical lower bound for the distance is on the order of 50 light years and a typical upper bound on proper motion is on the order of 0.1 seconds of arc per year. These measurements are limited by the noise on the arrival-time data.

The period characteristics of most pulsars are described quite well by a simple polynomial, i.e., a constant plus a linear term. The constant term corresponds to the period at some epoch and the linear term corresponds to the rate of change of the period. The uncertainty in the period determinations is typically a few parts in $10^{11}$ (a few hundredths of a nanosecond). The uncertainty in the rate of change determinations is typically a few parts in $10^3$ ($\sim 10^{-17}$ seconds per second). The accuracy in determining period characteristics is limited by noise on the time-of-arrival data and the length of the data span. There are two pulsars for which the linear model does not describe their period characteristics. They are discussed in the next section.

Definitive results have not been obtained in our attempts to measure relativistic effects. A highly correlated measurement of the gravitational red shift of the sun was obtained (Reference 7), which agrees with theory to within a few percent. The limitation on the measurement was the use of data from one pulsar only. By using as many pulsars as possible, the correlation of the result could be reduced significantly. An attempt was made to measure the time delay of the ticks of the pulsar clock as they passed through the sun's gravitational field. However, the accuracy in arrival time needed to make the measurement was not achieved. The basic limitation was noise on the data.

## Discussion

The noise on the data has been blamed for the basic limitation in the majority of the measurements discussed in the previous section. The noise

can be thought of as having two components, discrete and random. The random component is due to the random noise that is inherent in the received signal. This causes random errors in the measurements of the pulse arrival times. For pulsars with stronger signals, the discrete component of measurement error shows up. Since there is a limit to the speed at which the pulses can be sampled, the error then becomes dependent on the length of time between samples.

Currently, work is being done on methods in which to reduce the noise. The obvious solution to the discrete component is to sample at a rate fast enough such that the noise is indeed random. Therefore, equipment which will sample at a faster rate is being designed and constructed. The random noise can also be reduced somewhat. As mentioned in the introduction, the arrival times are estimated by correlating an approximate pulse shape with the data. These estimates can be improved by correlating with the true pulse shape. By adding all the pulses for a particular pulsar and using this as the "true" pulse shape, it is hoped that this improvement can be attained. Just such a technique is currently being worked on.

As mentioned in the last section, the limitation to angular position determination was the accuracy of the ephemeris, mainly the rate of precession. If the measurement accuracy of the data can be improved, then this limitation would disappear for then the rate of precession can be solved for.

The length of the data span was mentioned as the limitation in the determination of period characteristics. The solution to this, of course, is to take data for a long time. But this, then, opens the door to other unknowns which must be solved for. It has been observed that two pulsars do not have a period described by a linear period model. These two pulsars are described by higher-order polynomials. It is predicted that other pulsars will also exhibit this behavior. The measurement of the quadratic term, or second derivative, is important in determining the radiation process of pulsars. Our estimates show (Reference 2) that for some of the pulsars which are being observed, this effect should be observable after approximately 5 yr.

Another error source that will show up over a length of time is the uncertainty in planetary masses. Since the inertial frame used in the data reduction is solar system barycentric, it involves all the planetary masses. If there is significant error in a planet's mass, this effect will show itself in a period of time roughly comparable to half of the planet's period of revolution. Much care must be exercised in solving for these effects, especially the longer period ones. Galactic rotation could contribute similar effects. This means that measurements should be taken for at least two periods of a particular planet's orbit before an attempt is made to improve its mass determination.

As mentioned, there are two pulsars whose period characteristics are not described by linear polynomials. A more accurate description would be that they are not described by polynomials at all. The periods of the Crab Nebula pulsar and the Vela pulsar are not only not described by polynomials but also exhibit discrete jumps in their periods (see, for example, Reference 5). These effects are ideal for determining the physics of the pulsars themselves but make them very unreliable as pulsar clocks. These pulsars are believed to be much younger than other pulsars and to be in an unstable state. All the other pulsars have exhibited stable periods for the 3 yr that they have been under observation.

There are other applications of pulsars in determining the unknowns of the galaxy and the solar system. The observation of dispersive effects on the pulsar signals has yielded information on the electron content of the interstellar medium. The observations of scintillations on the signals has yielded information on the size and density of electron clouds and their movements. Some scintillation measurements have been made (Reference 8) and more are being planned.

It is concluded that the calibration of pulsar clocks is indeed a useful concept, and that there is a wealth of knowledge that can be gleaned in the process.

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